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# Climate stability during the Pliocene warm period

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[1] We present a high-resolution climate record from a sediment core spanning an 80-kyr interval of time during the mid-Pliocene epoch, when warmer conditions and lower global ice volume prevailed worldwide. Oxygen and carbon isotope analyses were made on benthic and planktonic foraminifera from ODP Site 981 in the North Atlantic. The amplitude and approximate recurrence interval of suborbital variations in these records are comparable to those of Holocene and marine isotope stage 11 (MIS 11) records from the North Atlantic. We conclude that the mid-Pliocene warm interval was a time of relative climatic stability. These results suggest that warmer climatic conditions alone may not necessarily enhance variability in the climate system, a finding that may facilitate predictions of 21st century climatic response to anthropogenic warming. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1635 Global Change: Oceans (4203); 3030 Marine Geology and Geophysics: Micropaleontology; 4267 Oceanography: General: Paleoceanography; 9325 Information Related to Geographic Region: Atlantic Ocean; *KEYWORDS:* millennial variations, interglacial, Pliocene warm period, North Atlantic climate

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## 1. Introduction

### 1.1. Millennial-Scale Climate Variability

[2] The past two decades of climate research have resulted in a greatly improved understanding of the timescales over which climatic variations occur. It is now well established that Earth's climate varies in regular cycles driven by changes in insolation; the three major periods of oscillation (eccentricity, obliquity, and precession) predicted by *Milankovitch* [1930] are readily evident in paleoclimate records [*Hays et al.*, 1976; *Imbrie et al.*, 1984]. In recent years, many climate proxies have also yielded evidence of fluctuations on suborbital timescales. Millennial-scale temperature oscillations during the late Pleistocene have been documented in ice cores from Greenland and Antarctica (e.g., Dansgaard-Oeschger cycles; *Dansgaard et al.* [1984, 1993], *Johnsen et al.* [1992]). Deep-sea sediment cores reveal similarly paced variations in sea surface temperature (SST), ice-rafted debris (IRD), and thermohaline circulation in late Pliocene through Holocene records [e.g., *Heinrich*, 1988; *Bond et al.*, 1993; *Bond and Lotti*, 1995; *Oppo and Lehman*, 1995; *Bond et al.*, 1997; *Raymo et al.*, 1998; *Bianchi and McCave*, 1999; *Chapman and Shackleton*, 2000; *McIntyre et al.*, 2001].

[3] While climatic variations on millennial timescales have been observed in widely distributed records [e.g., *Bender et al.*, 1994; *Hughen et al.*, 1996; *Behl and Kennett*, 1996; *Lund and Mix*, 1998; *Blunier et al.*, 1998], their effects are most prominent, and have been most thoroughly studied, in the North Atlantic. There climate proxies show periodic fluctuations throughout the Holocene and late Pleistocene "100-kyr world," when major glacial/interglacial cycles have occurred on the timescales of approximately 100 kyr, and also in the "41-kyr world" of the early Pleistocene and late Pliocene when glacial cycles occurred with almost metronome-like regularity paced by obliquity [*Raymo et al.*, 1998; *McIntyre et al.*, 2001]. Multiple studies have shown a ~1500-year period of oscillation within Holocene and Pleistocene climate records [*Bond et al.*, 1997; *Mayewski et al.*, 1997; *Grootes and Stuiver*, 1997; *Campbell et al.*, 1998; *Bianchi and McCave*, 1999; *Schulz*, 2002] as well as longer-period (2–7 kyr) cycles [e.g., *Dansgaard et al.*, 1993; *Bond et al.*, 1997].

[4] Although no clear origin for millennial-scale climate change is accepted at this time, several possible causes for variations at these periods have been proposed, including ice sheet dynamics [*MacAyeal*, 1993], complex ocean-atmosphere interactions [e.g., *Cane and Clement*, 1999; *Alley et al.*, 1999], and aliasing of a higher-frequency climate cycle [*Wunsch*, 2000]. *Wara et al.* [2000] attributed millennial-scale fluctuations in the North Atlantic between 200–600 ka to harmonics of Milankovitch insolation cyclicity produced by interactions with Northern Hemisphere atmosphere, oceanic, and ice mechanics. A study by *Bond et al.* [2001] showed a correlation between solar activity inferred


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from cosmogenic nuclides and centennial to millennial variations in North Atlantic IRD during the Holocene, suggesting solar forcing as a cause for the 1500-year cycle. A link between Holocene polar winds, North Atlantic IRD, and deepwater fluctuations in the North Atlantic has also been suggested [*Oppo et al.*, 2003], indicating possible thermohaline amplification of millennial-scale climate change. Finally, *Schulz* [2002] showed a recurrence interval of ~1500 years in three Dansgaard-Oeschger (D-O) events in the Greenland Ice Sheet Project 2 (GISP2) ice core, and proposed that the 1500-year spectral peak was caused by the pacing of only those three interstadial events; new analyses imply that this 1500-year cycle may be more pervasive in GISP2 however [*Rahmstorf*, 2003].

[5] Many of the aforementioned studies indicate that climate variations on millennial timescales have existed for at least as long as the rhythmic glacial/interglacial cycles of the Holocene and Pleistocene have persisted. This suggests that suborbital fluctuations might be a ubiquitous feature of Earth's climatic history, with amplitude modulated by lower frequency glacial-interglacial transitions. In order to assess the validity of that idea, we have investigated high-frequency climate variability during a period of prolonged climate warmth, prior to the onset of large-scale Northern Hemisphere glaciation at ~2.5 Ma [*Shackleton et al.*, 1984]. The objective of this study was to evaluate the amplitude and recurrence interval of millennial-scale climatic variability during a warmer period in Earth's history when no large glacial/interglacial cycles occurred and global ice volume was relatively low, the mid-Pliocene "climatic optimum." *McManus et al.* [1999, 2003] predicted that conditions such as these would promote millennial-scale climatic stability while other studies [e.g., *Manabe and Stouffer*, 1993; *Rahmstorf and Ganopolski*, 1999] have predicted that enhanced precipitation at higher latitudes in a warmer world could enhance thermohaline (and hence regional climate) instability.

[6] Characterizing climatic behavior during a time of prolonged warm conditions and low ice volume in the past may also provide clues to the potential consequences of anthropogenic warming imposed on the modern environment. A comparison of the amplitude and pacing of suborbital variability in climate proxies from time intervals representing different background conditions (global temperature and ice volume) provides a useful indication of climatic tendency toward relative stability or instability on such timescales.

#### 1.1.1. Millennial-Scale Variations During Glacial Intervals

[7] Millennial-scale climatic oscillations during late Pleistocene glacial episodes include D-O variations in air temperature over Greenland with an amplitude of more than 8°C [*Johnsen et al.*, 1992]. Periods of oscillation may vary from 1–4 kyr (for D-O events and SST cycles) [e.g., *Johnsen et al.*, 1992; *Dansgaard et al.*, 1993] to 6–10 kyr (for Heinrich ice rafting events) [*Heinrich*, 1988; *Broecker et al.*, 1992; *Bond et al.*, 1993]. North Atlantic SST varied by >4°C on timescales of 1–4 kyr during late Pleistocene ice growth and by ~3°C during glacial episodes [*Oppo et al.*, 1998].

[8] Similarly paced variability has been demonstrated in older glacial cycles within North Atlantic sedimentary sequences. *Raymo et al.* [1998] showed millennial-scale instability in surface and deep-water records during two glacial-interglacial cycles from the high-latitude Gardar Drift (ODP Site 983) at ~1.3 Ma. *McIntyre et al.* [2001] expanded the Site 983 record to include the late Pliocene, during which IRD events and variations in deep-water circulation were found to occur every 2–5 kyr during glacial intervals, comparable to the frequency of D-O events in Late Pleistocene Greenland ice records. Late Pliocene and early Pleistocene glacial intervals do not appear to show IRD events with a recurrence interval of 6–10 kyr, the pacing of late Pleistocene Heinrich events, implying that the larger Heinrich events are unique to the "100-kyr world" of late Pleistocene major ice sheet growth [*McIntyre et al.*, 2001].

#### 1.1.2. Millennial-Scale Variations During Interglacial Intervals

[9] The amplitude of millennial-scale climatic variability is substantially reduced during interglacial intervals relative to times of glaciation and ice sheet growth and decay [*Oppo et al.*, 1998; *McManus et al.*, 1999, 2003; *McIntyre et al.*, 2001]. Though suborbital variations have been detected in Holocene and late Pleistocene interglacial records [e.g., *Bond and Lotti*, 1995; *Bond et al.*, 1997; *Alley et al.*, 1997; *Oppo et al.*, 1998, 2003], warm intervals appear, generally, to be relatively stable on such timescales [e.g., *Broecker et al.*, 1990; *McManus et al.*, 1999]. Millennial-scale variability shows the same pacing, statistically, in glacial and interglacial records [*Bond et al.*, 1997].

[10] Holocene air temperature oscillations with a typical amplitude of 2–3°C have occurred over Greenland on millennial timescales [*Johnsen et al.*, 1992; *Alley et al.*, 1997]. Late Pleistocene interglacial SST oscillations occur in the North Atlantic with 3–4 kyr pacing, but with an amplitude of only 0.5–1°C, reflecting a more stable surface hydrography compared to glacial intervals [*Oppo et al.*, 1998]. Late Pliocene and early Pleistocene records [*McIntyre et al.*, 2001] indicate variation in benthic $\delta^{18}O$ with ~2 kyr pacing, though with lower amplitude than during glacial episodes from the same region. Consistent differences in the amplitude of suborbital variations during Pleistocene glacial and interglacial stages led *McManus et al.* [1999] to propose that millennial-scale climatic instability prevails when ice sheet volume exceeds a threshold, estimated to be 20–50 m of sea-level decrease relative to the modern level.

### 1.2. Mid-Pliocene Warm Period

[11] The mid-Pliocene is an ideal interval in which to investigate prolonged warm conditions at high resolution. This period is the most recent in geologic time with temperatures comparable to those projected for the 21st century [e.g., *Dowsett et al.*, 1994]. The configuration of oceans and continents at 3 Ma is similar to today, allowing feasible comparison of oceanic and atmospheric conditions in models of Pliocene and modern climate [e.g., *Chandler et al.*, 1994]. Pliocene environmental estimates based on microfossils are likely to be more accurate than pre-Pliocene studies as many Pliocene species (marine and terrestrial) still exist today [*Dowsett et al.*, 1992].

[12] Evidence is abundant for widespread warmth during this epoch. At 3.0 Ma, high-latitude SSTs may have been elevated by as much as 7°C with respect to modern values, and midlatitude SSTs by 3–4°C with respect to modern values; estimates of low-latitude SSTs from that time show no significant difference from the present [*Dowsett and Poore*, 1991; *Dowsett et al.*, 1992, 1994, 1999]. Atmospheric carbon dioxide may have been up to 35% higher than preindustrial levels [*Raymo et al.*, 1996]. Stronger thermohaline circulation has been proposed to explain increased meridional transport of heat to high latitudes in the Atlantic; the equator-pole gradient of surface temperature was less than the modern gradient [*Dowsett et al.*, 1992, 1994; *Chandler et al.*, 1994]. Enhanced thermohaline transport of heat to high latitudes may have provided a positive feedback mechanism that kept climate warm by inhibiting formation of sea ice [*Raymo et al.*, 1996]. Faunal assemblages indicate ice-free conditions over most or all of the Arctic Ocean [*Cronin et al.*, 1993; *Dowsett et al.*, 1999]. Modeling studies indicate that surface wind strength over the North Atlantic, North Pacific and Southern Ocean were greater than today, implying that geostrophic gyre circulation may have been enhanced during the mid-Pliocene [*Haywood et al.*, 2000, 2002].

[13] Glaciers were extant in Greenland and Scandinavia during this time, evident from very small amounts of IRD in cores from the Vøring Plateau and off the coast of East Greenland [*Jansen et al.*, 1990]. However, the absence of any significant IRD peaks in North Atlantic sediment before 2.5 Ma suggests that no widespread Northern Hemisphere glacial advances took place during the mid-Pliocene [*Shackleton et al.*, 1984; *Raymo et al.*, 1989; *Jansen et al.*, 1990; *Jansen and Sjøholm*, 1991; *Channell et al.*, 1999]. Sea level during the mid-Pliocene has been estimated at 35 ± 18 m higher than modern sea level [*Dowsett and Cronin*, 1990], subsequently revised to ~25 m above modern sea level [*Dowsett et al.*, 1999]. Because Antarctic ice accounts for all but 5–10 m of the modern sea-level depression [*Williams and Ferrigno*, 1999], this substantially elevated sea level suggests significant melting of the Antarctic ice cap [*Dowsett et al.*, 1999]. Paleontological evidence indicating marine conditions in the Antarctic interior [*Webb and Harwood*, 1991] is consistent with mid-Pliocene Antarctic ice sheet retreat, as is extensive paleosol development [e.g., *Retallack et al.*, 2001], although these interpretations are controversial [e.g., *Burckle et al.*, 1996]. The warm conditions that prevailed during the mid-Pliocene began to decline by 2.7 Ma with marine and terrestrial records indicating global cooling, which at 2.5 Ma culminated with significant ice growth in the circum-North Atlantic region (marine isotope stage 100).

### 1.3. ODP Sites 980/981

[14] We selected for high-resolution study a North Atlantic sedimentary record from Ocean Drilling Program Site 981 (Figure 1) that spans the mid-Pliocene (~3.1 to 3.3 Ma). Site 981, located at 55° 29′N, 14° 39′W, in a water depth of 2200 m, was drilled into the Feni Drift on the southeast side of the Rockall Plateau. The Feni Drift is a site of rapid sediment accumulation where deep water carrying a high volume of suspended sediment flows south from the Norwegian Sea and deposits fine-grained sediment in a region of low current activity. The high-resolution record provided by the rapid sedimentation rate at this site has the potential to allow millennial-scale climate change, if present, to be resolved and analyzed in detail.

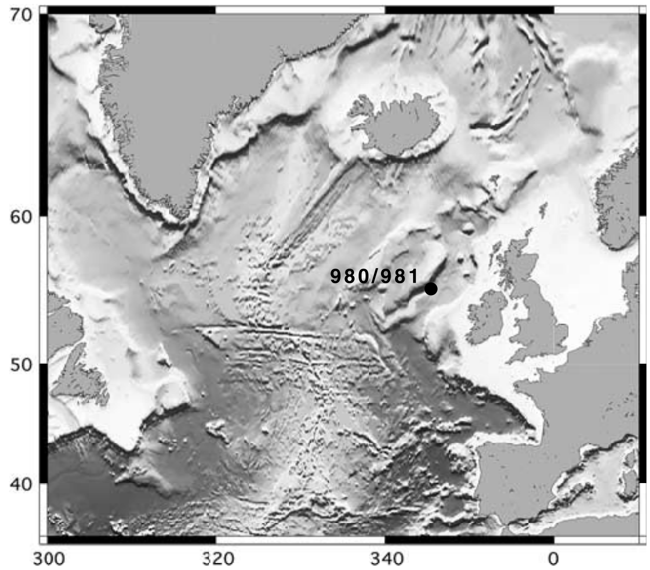


**Figure 1.** Locations of Ocean Drilling Program Sites 980 and 981.

[15] Ocean Drilling Program Sites 980 and 981 share essentially the same location (Figure 1); the core from Site 980 captures high sedimentation rates during the Mid-Pleistocene to Holocene while Site 981 was drilled in sediment that accumulated more rapidly during the Pliocene and Early Pleistocene. The proximity of these two sites (3.7 km) allows a high-resolution comparison of conditions at various times at the same location over the past 4 Myr.

## 2. Methods

[16] We first analyzed a low-resolution (30-cm sampling interval) benthic foraminiferal $\delta^{18}O$ record from Site 981 that had been generated at the Massachusetts Institute of Technology (MIT) [*Flower et al.*, 2000; M. E. Raymo et al., Stability of North Atlantic water masses in face of pronounced natural climate variability, submitted to *Paleoceanography*, 2003, hereinafter referred to as Raymo et al., submitted manuscript, 2003]. Although no paleomagnetic stratigraphy exists for Site 981 below the Pleistocene, we established an age scale for this low-resolution record by correlating the $\delta^{18}O$ record to DSDP Site 607 (western Atlantic), which has a benthic $\delta^{18}O$ record dated by paleomagnetic age datums [*Berggren et al.*, 1995]; this age model is hereafter referred to as 607PMAG. The 981 record was matched to 607PMAG by graphical correlation of peaks in the benthic $\delta^{18}O$ records using Analyseries software [*Paillard et al.*, 1996]. Figure 2 shows this low-resolution record of benthic $\delta^{18}O$ from ODP Site 981 and

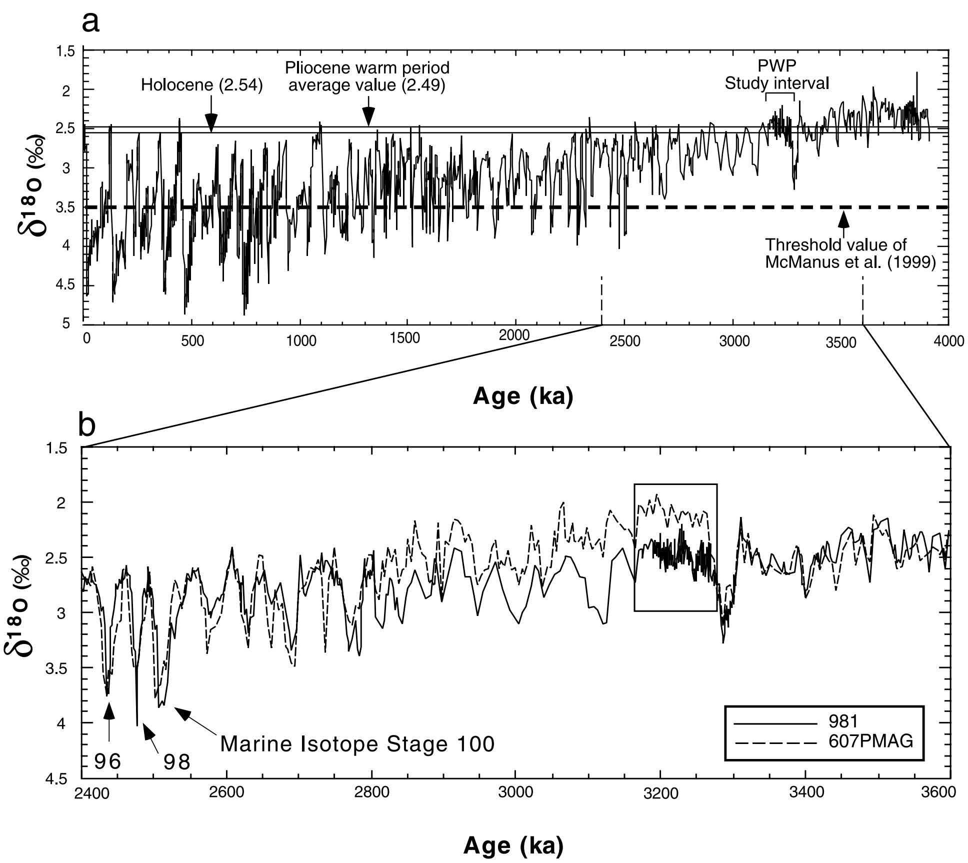


**Figure 2.** (a) Benthic $\delta^{18}$O record for ODP Sites 980 and 981 (*C. wuellerstorfi*) based on correlation with the 607PMAG timescale. Data from 0–850 kyr are from Site 980 [*Oppo et al.*, 1998; *McManus et al.*, 1999]. Data below 850 kyr are from Site 981 [*McIntyre et al.*, 2001; this study]. The Pliocene warm interval selected for high-resolution study is indicated by a bracket. Black horizontal lines mark the $\delta^{18}$O values from the mid-Pliocene warm interval and the Holocene (average of 0–5 ka). The dashed horizontal line indicates the 3.5‰ threshold value of *McManus et al.* [1999], above which larger amplitude millennial-scale climate variations are observed. Long-term trends toward cooler climate and frequent glacial events are apparent in this record. (b) ODP Site 981 benthic $\delta^{18}$O data compared with benthic $\delta^{18}$O record from DSDP Site 607 for the 2.4–3.6 Ma interval [e.g., *Raymo et al.*, 1989]. The 607PMAG timescale [*Berggren et al.*, 1995] was used to generate the 981 age model by graphical correlation. The mid-Pliocene warm interval chosen for high-resolution study is indicated by the box. Marine isotope stages 96, 98, and 100 (the first major Northern Hemisphere glaciations of the Pliocene) are shown for reference [*Shackleton and Hall*, 1984; *Keigwin*, 1986].

the adjacent Site 980. The tie points used to link the 981 record to the 607PMAG timescale do not result in any abrupt changes in sedimentation rate at Site 981.

[17] Once the age scale was established, we selected an interval for a high-resolution study that encompassed the warmest temperatures of the mid-Pliocene. This was the same time interval studied as part of the USGS-sponsored PRISM project and used to generate SST models for the Pliocene [e.g., *Dowsett et al.*, 1994, 1999; *Chandler et al.*, 1994]. Figure 2b shows the 981 and 607 records from 2.4 to 3.6 Ma, with the high-resolution study area and relevant age-control points indicated. The selected study interval from the 981 core was sampled every 3 cm, with each sample spanning 2 cm. The ~110 kyr interval between age-control points on either side of the mid-Pliocene warm interval is represented by a 1300-cm section of sediment. The simplifying assumption that sedimentation rate is constant yields an accumulation rate within the high-resolution study interval of 11.7 cm/kyr, or 1 cm per 85.4 years. Each discrete sediment sample therefore represents approximately 171 years, with a sample spacing of approximately 256 years. The sampling resolution (distance between mid-points of two samples) is therefore approximately 427 years. With a highly accurate timescale, this sampling interval would allow resolution of periodicity at ~1 kyr and longer. However, our ability to draw conclusions about periodicity in these data is restricted by uncertainty in age models for time intervals older than 50 ka, which lie beyond the range within which radiocarbon dating can be used to verify age models that are based on orbital tuning or paleomagnetic reversals. We do expect to be able to resolve statistically significant variations with the periods of Dansgaard-

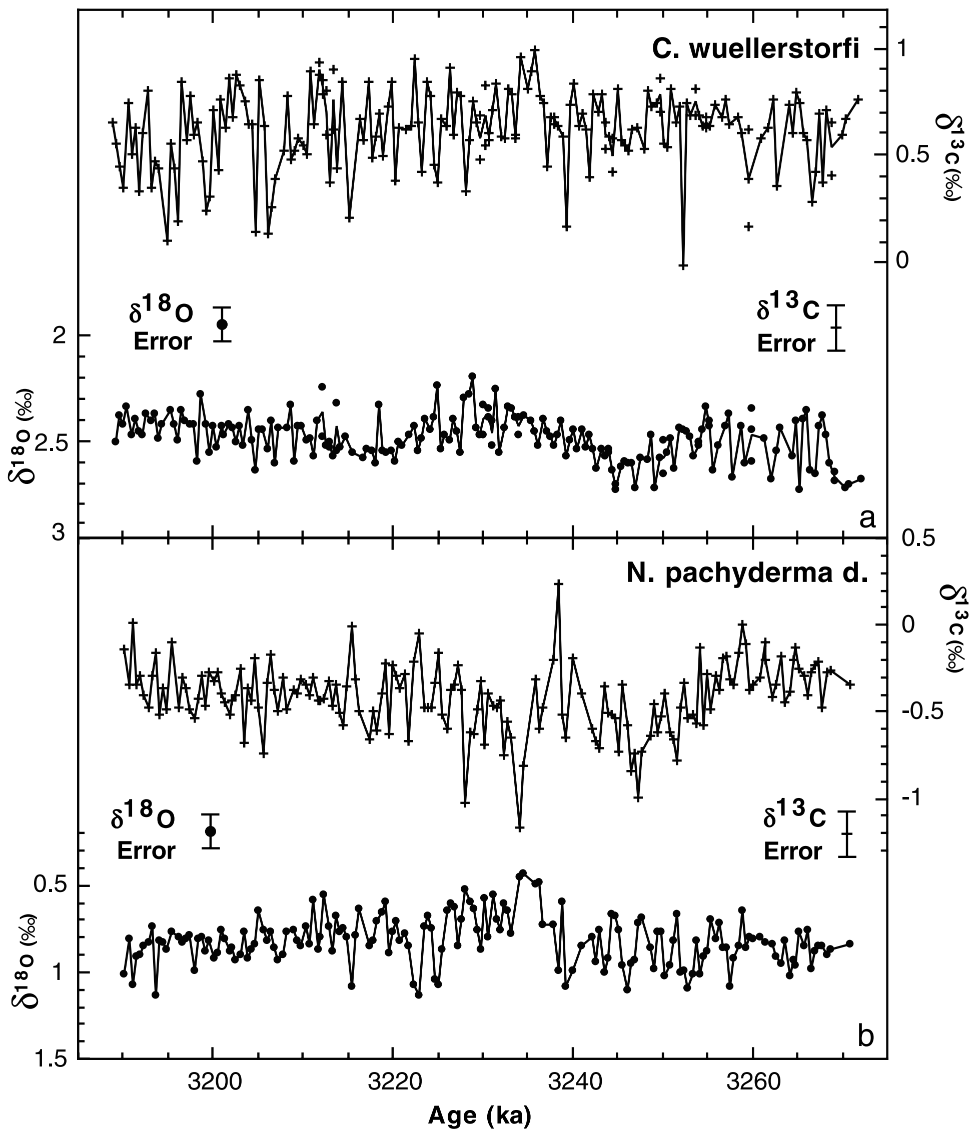


**Figure 3.** (a) Site 981 high-resolution benthic data from the Pliocene warm period (*C. wuellerstorfi*). (b) Site 981 high-resolution planktonic data from the Pliocene warm period (*N. pachyderma-d.*).

Oeschger cycles or Heinrich events had they been preserved in this rapidly accumulating sedimentary record.

[18] Samples were washed and from the size fraction greater than 150 μm, benthic and planktonic foraminifera (*Cibicidoides wuellerstorfi* and *Neogloboquadrina pachyderma* dextral-coiling, respectively) were collected. *C. wuellerstorfi* is widely used as a reliable recorder of deep-water oxygen and carbon isotope chemistry [e.g., *Shackleton and Opdyke*, 1973; *Shackleton and Hall*, 1984; *Curry et al.*, 1988] while *N. pachyderma d.* has been used to record those parameters in surface water [e.g., *Duplessey et al.*, 1988; *Oppo et al.*, 1998]. $\delta^{18}$O and $\delta^{13}$C were measured by mass spectrometry at MIT. Isotope values are calibrated to the Pee Dee belemnite (PDB) standard using the NBS-19 carbonate standard ($\delta^{18}$O = −2.2 VPDB, $\delta^{13}$C = 1.95 PDB). Standard deviation of the isotope values for NBS-19 is ±0.08‰ for $\delta^{18}$O and ±0.04‰ for $\delta^{13}$C. Analyses of benthic foraminifera typically contained between 4 and 10 specimens, while analyses of planktonic foraminifera contained between 20 and 25. In samples containing enough foraminifera of the desired species, multiple isotope analyses were obtained. For the 16 samples on which multiple analyses were made, the average standard deviation for $\delta^{18}$O measurements is 0.06‰, and for $\delta^{13}$C the average standard deviation is 0.11‰.

[19] Spectral analysis using Blackman-Tukey methods [*Jenkins and Watts*, 1968] was performed on benthic and planktonic $\delta^{18}$O and $\delta^{13}$C using Analyseries spectral analysis software [*Paillard et al.*, 1996]. Cross-spectral analyses were also made between pairs of each of the four data sets:

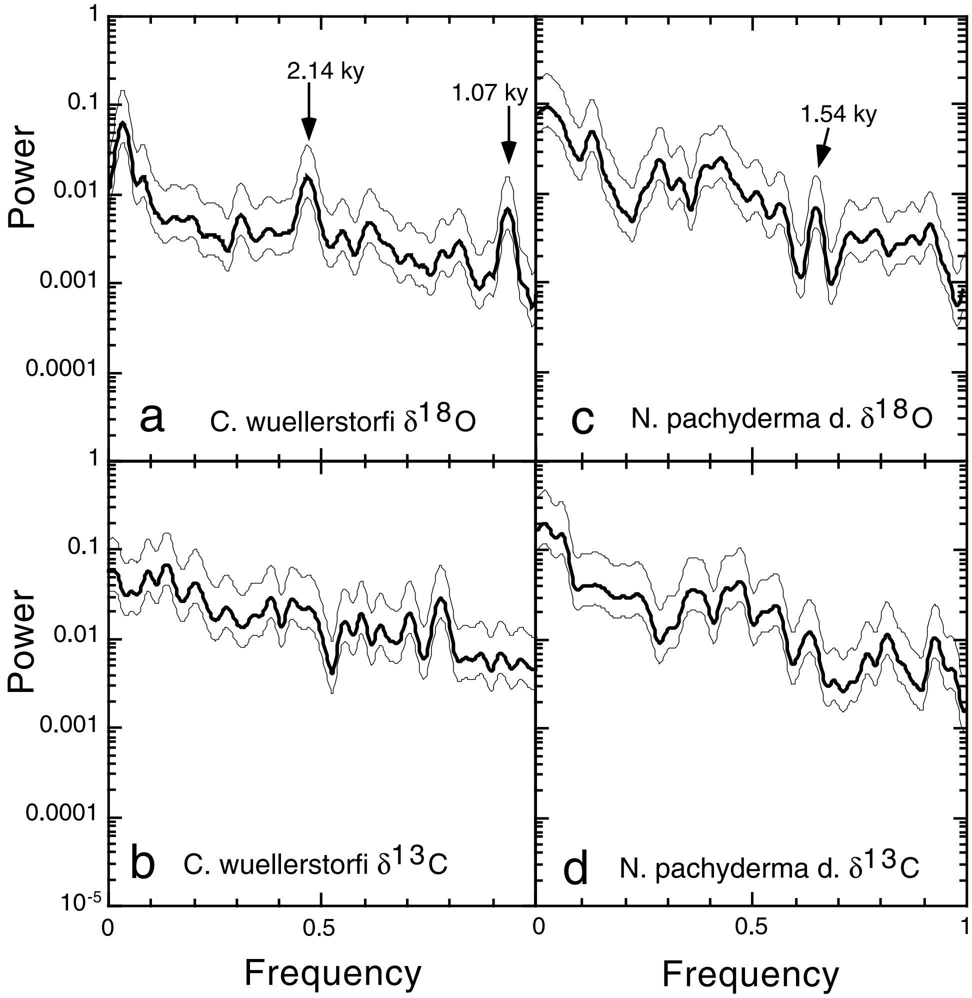


**Figure 4.** (a) Spectral analysis of high-resolution benthic $\delta^{18}O$ data. Upper and lower bounds on either side of the bold data line are shown for the 90% confidence interval in each of the four plots in Figures 4a–4d. In all four plots, a Bartlett window has been used to treat edge effects. Bandwidth in Figures 4a and 4b is 0.0476. (b) Spectral analysis of high-resolution benthic $\delta^{13}C$ data. (c) Spectral analysis of planktonic $\delta^{18}O$ data. Bandwidth in Figures 4c and 4d is 0.0484. (d) Same as Figure 4c, but for planktonic $\delta^{13}C$ data.

benthic $\delta^{18}O$, benthic $\delta^{13}C$, planktonic $\delta^{18}O$, and planktonic $\delta^{13}C$.

## 3. Results

[20] The results of benthic and planktonic $\delta^{18}O$ and $\delta^{13}C$ analyses in the mid-Pliocene interval studied at high resolution are shown in Figure 3. Data are available from the NOAA World Data Center-A for Paleoclimatology at http://www.ngdc.noaa.gov/paleo. For samples on which multiple analyses were performed, the line showing isotope trends passes through the average values. The error margins (±) are determined by the largest analytical error for $\delta^{18}O$ and $\delta^{13}C$; 0.08‰ for $\delta^{18}O$, from analysis of standards, and 0.11‰ for $\delta^{13}C$, from replicate analysis of 16 samples (error bars are thus ~0.16‰ wide for $\delta^{18}O$, ~0.22‰ wide for $\delta^{13}C$). Results of spectral analyses are shown in Figure 4. Cross-spectral analyses (not shown) showed no coherence between any of the four data sets.

[21] The records resolve fairly low-amplitude millennial-scale oscillation in benthic and planktonic $\delta^{18}O$ and $\delta^{13}C$. The sum of the mass spectrometry and data reproducibility error margins generates error bars that encompass most of the high-frequency variation observed in our data, as shown in Figure 3. The higher standard deviation of replicate analyses observed in $\delta^{13}C$ compared to $\delta^{18}O$ analyses suggests that $\delta^{13}C$ in *C. wuellerstorfi* is inherently more "noisy" than $\delta^{18}O$, resulting in error bars of similar width for $\delta^{13}C$ and $\delta^{18}O$ even though the accuracy of mass spectrometer measurements of $\delta^{13}C$ is greater than $\delta^{18}O$.

[22] The benthic $\delta^{18}O$ record, a proxy that varies with bottom-water temperature, salinity, and global ice volume, reveals nonperiodic high-frequency variation superimposed upon a pattern with longer wavelength. The amplitude of the high-frequency fluctuations is variable but reaches a maximum of approximately 0.3‰. The amplitude of long-wavelength variability is slightly less, around 0.2‰. The average $\delta^{18}O$ value of 2.49‰ throughout this high-resolu-

tion interval is 0.05‰ lower than that measured for the top of the Site 980 core (2.54‰ for an average from 0 to 5 ka). The amplitude of this high-frequency variability does not appear consistent nor do the patterns appear cyclic. Notable differences are apparent between the benthic $\delta^{18}O$ and benthic $\delta^{13}C$ records shown in Figure 3a. Benthic $\delta^{13}C$, a proxy for deep-water nutrient chemistry [e.g., *Curry et al.*, 1988], does not display the low-frequency trends seen in $\delta^{18}O$, and high-frequency fluctuations in this record do not correlate with the high-frequency variations seen in $\delta^{18}O$. Here also, the amplitude of high-frequency variation rarely exceeds the error range on these $\delta^{13}C$ measurements. The maximum amplitude of high-frequency $\delta^{13}C$ variation is on the order of 0.7‰. The average benthic $\delta^{13}C$ value of 0.62‰ throughout this interval is 0.36‰ lighter than the Site 980 core-top (0–5 ka average) value of 0.98‰.

[23] Figure 3b shows planktonic data for this interval. As in the benthic record, $\delta^{18}O$ and $\delta^{13}C$ show low-amplitude millennial-scale variations, which remain largely within the error margin. The $\delta^{18}O$ signal from *N. pachyderma d.* has been used as a proxy for SST; in this record, it displays high-frequency variation with a recurrence interval that varies between ~1–4 kyr. Planktonic $\delta^{18}O$ has maximum amplitude variations of up to 0.7‰ over less than 1000 years, but most fluctuations are on the order of 0.1–0.3‰. Subtle low-frequency variation is evident, with an amplitude of approximately 0.25‰. A similar long-wavelength cycle is apparent but subtle in the planktonic $\delta^{13}C$ record, and high-frequency fluctuations are evident with an amplitude of up to 1.2‰ in the largest-amplitude cycle (between 3240 and 3246 kyr). $\delta^{18}O$ values average 0.82‰, or 0.4‰ lighter than the core-top (0–5 ka average) value of 1.22‰ for *N. pachyderma d.* at Site 980. Planktonic $\delta^{13}C$ within the Pliocene warm period interval averages −0.41‰, more than 0.6‰ lighter than the average Site 980 core-top (0–5 ka) value of 0.25‰.

## 4. Discussion

### 4.1. Benthic and Planktonic $\delta^{18}O$ and $\delta\ ^{13}C$ Variation: Significance

[24] Within the high-resolution mid-Pliocene interval, the average benthic $\delta^{18}O$ value is lighter than Holocene core-top benthic $\delta^{18}O$ by ~0.05‰. A global ocean $\delta^{18}O$ decrease of this magnitude suggests a sea-level rise of approximately 5 m, substantially less than the ~25 m inferred for the Pliocene warm period by *Dowsett and Cronin* [1990] and *Dowsett et al.* [1999]. The average planktonic $\delta^{18}O$ value observed in our Pliocene interval is 0.4‰ lighter than planktonic core-top $\delta^{18}O$. Such light planktonic $\delta^{18}O$ could arise from a 5 m sea-level difference coupled with a Pliocene SST approximately 1.2°C above the modern temperature. This is not consistent with other estimates of high-latitude SST during the Pliocene warm period that have suggested temperatures up to 7°C higher than modern values [*Dowsett and Poore*, 1991; *Dowsett et al.*, 1992]. Multiple lines of evidence have demonstrated that the mid-Pliocene was a time of elevated global temperature and sea level. However, not all marine sites show significantly lighter Pliocene benthic $\delta^{18}O$ relative to Holocene values (e.g., Ceara Rise sites of *Tiedemann and Franz* [1997] and Site 981 [this study]). This indicates that regional changes in deepwater temperature and/or salinity have occurred at these sites that have offset their Holocene values relative to those of the mid-Pliocene. This is not expected to compromise the ability of benthic foraminiferal isotopes at Site 981 to record millennial variability, unless such processes also occurred on millennial timescales. Alternatively, published faunal planktonic SST estimates [*Dowsett and Poore*, 1991; *Dowsett et al.*, 1992] could be inaccurate due to species evolution and possible development of isotope-fractionating vital effects in *N. pachyderma d.* since the Pliocene warm period.

[25] The high frequency variation in benthic $\delta^{18}O$, within our Pliocene interval, could have several possible causes. A change of 0.3‰ in $\delta^{18}O$, the maximum amplitude of benthic $\delta^{18}O$ variation in our data, could correspond to a temperature change of slightly greater than 1°C [*Epstein et al.*, 1953; *Emiliani*, 1955] or to a change in global ice volume corresponding to a sea-level change of approximately 30 m within each $\delta^{18}O$ peak [*Fairbanks and Matthews*, 1978]. The latter explanation seems highly unlikely; although rates of sea-level rise as high as 26 m/kyr have been inferred for short periods of time during the last deglaciation [*Fairbanks*, 1989], that rate of sea-level rise is anomalously rapid. The absence of North Atlantic IRD peaks, and the observation that the Pliocene $\delta^{18}O$ shifts do not resemble those of asymmetric glacial/interglacial transitions, further imply that global sea-level change did not cause the high-frequency $\delta^{18}O$ variation in this record. Additionally, benthic and planktonic $\delta^{18}O$ do not covary (Figure 3), indicating that the ocean reservoir $\delta^{18}O$ is not changing as would be expected if the signal was driven by changing ice volume. Other possible explanations for high-frequency benthic $\delta^{18}O$ fluctuation, including frequent temperature variations with an amplitude of 1°C or mixing of waters of different salinity at this site, are more plausible but we consider it unnecessary to invoke such processes because much of the amplitude of benthic $\delta^{18}O$ variation is within the error margin on these data.

[26] It is not clear why planktonic $\delta^{13}C$ is substantially lighter (by 1.03‰, on average) than the benthic $\delta^{13}C$. Given that the benthic carbon isotopic signal is believed to be derived from the surface $\delta^{13}C$ value as surface water sinks to form North Atlantic Deep Water (NADW), benthic $\delta^{13}C$ is expected to be similar to planktonic $\delta^{13}C$, or to be lighter than the planktonic value due to enrichment of $^{12}C$ in deeper water from the decay of organic matter. Similar disparity between benthic and planktonic $\delta^{13}C$ is present in other North Atlantic and Norwegian Sea records [*Keigwin*, 1986; *Duplessy et al.*, 1988) and throughout the past 500 ka at Site 980. Vital effects are not known to affect $\delta^{13}C$ values of *C. wuellerstorfi*; this offset may be due to fractionation of carbon isotopes by *N. pachyderma d*. with a vital effect comparable to that of *N. pachyderma s*. [*Bauch et al.*, 2002].

### 4.2. Periodicity of Millennial-Scale Variation?

[27] We present the results of spectral analysis on these mid-Pliocene data in the interest of thorough discussion,

while recognizing that the limits of our sampling interval and Pliocene age models preclude confident identification of millennial cyclicity in these records. Several small peaks appear in the benthic $\delta^{18}O$ record, with frequency corresponding to periods of ~2 kyr and ~1 kyr (Figure 4a). These fall within the 1–4 kyr range observed for D-O variations during late Pleistocene glacial intervals. These results indicate that some suborbital variation does occur within these records, but given the irregular patterns and wide error margins shown in Figure 3a, and in view of the limitations of age models in a record as old as this, we cannot say with certainty that the variations are cyclic. Benthic $\delta^{13}C$ shows no spectral peaks that are considered statistically significant at the 90% level.

[28] A few statistically significant spectral peaks are observed in the planktonic records. $\delta^{18}O$ shows variation with a period of 1.5 kyr, similar to the pacing of D-O events [e.g., *Mayewski et al.*, 1997]. That is the only significant peak close to periods that characterize late Pleistocene records, including Site 980 [e.g., *Oppo et al.*, 1998]. Our planktonic $\delta^{13}C$ data show no spectral peaks that could be considered significant at the 90% level. Cross-spectral analyses failed to yield coherence between any of the four data sets.

[29] Higher-frequency climate oscillations might be resolved using a more closely spaced sampling interval. However, attaining higher resolution with a shorter sampling interval would prove difficult given the paucity of benthic foraminifera even in areas with high sedimentation rates. Resolution of true climate cycles longer than 1 kyr is not significantly hindered by bioturbation at Site 980/981 [*Berger and Heath*, 1968]. A typical mixing depth of 8–10 cm [*Berger and Johnson*, 1978; *Goreau*, 1980; *Schiffelbein*, 1984; *Boudreau*, 1994] precludes resolution of cycles oscillating with a period of less than ~850 years (the amount of time represented by 10 cm of sediment). Because Pliocene age models beyond the range of verification by radiocarbon dating are unlikely to be more accurate than 1 kyr, the further uncertainty imposed by bioturbation is relatively insignificant.

[30] The dependence of suborbital event spacing upon the choice of a specific age model must be considered. Age control points used in this study resulted from ~25 iterations performed to correlate the 981 record with the 607PMAG timescale. We used the most visually accurate correlation without invoking abrupt changes in sedimentation rate. To test the sensitivity of the pacing of millennial-scale variability to the age model, we also correlated the low-resolution benthic $\delta^{18}O$ pattern of Sites 980/981 to an astronomically tuned composite benthic $\delta^{18}O$ record (see http://131.111.44.196/coredata/v677846.html) instead of to 607PMAG. That correlation results in an age model virtually identical to that made from 607PMAG; spectral peaks in our high-resolution interval differ from those obtained using 607PMAG by an average of 1.6%. Using another astronomically tuned $\delta^{18}O$ record from ODP Site 846 (S. Clemens, unpublished timescale) as the reference timescale for a 981 age model also produced a spectral pattern very similar to that resulting from comparison with 607PMAG. We therefore consider the pacing of events within our data to be largely independent of biases inherent to the reference age model.

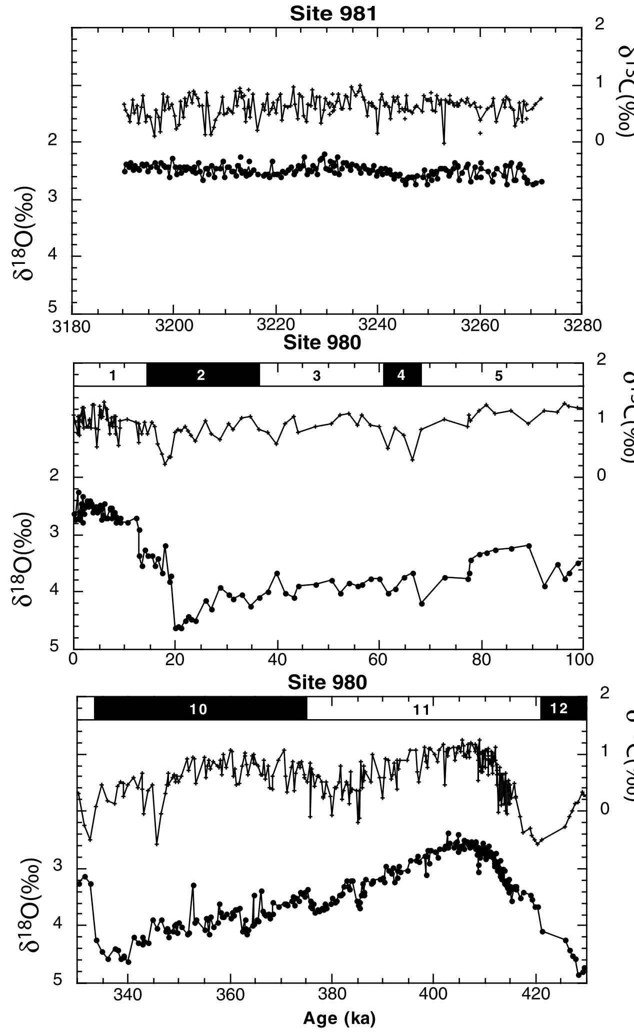


**Figure 5.** Comparison of benthic data from 100 kyr sections of Sites 980 and 981 (Site 980 data have previously been published by *Oppo et al.* [1998] and *McManus et al.* [1999]). Marine isotope stage (MIS) numbers are shown for reference in the two 980 plots. While amplitude of $\delta^{18}O$ variations in the mid-Pliocene record is negligible relative to those that mark the transition from glacial to interglacial episodes, the amplitude of $\delta^{13}C$ variations in the mid-Pliocene warm period is similar to that of $\delta^{13}C$ variability during glacial/interglacial cycles. Benthic $\delta^{13}C$ variability on multiple timescales thus appears relatively insensitive to background climate state (temperature or ice volume).

### 4.3. Comparison of the Mid-Pliocene With Glacial Intervals

[31] Here we compare the amplitude, and approximate recurrence interval, of events in this Pliocene record to high-resolution intervals studied from late Pliocene and Pleistocene glacial records. Figure 5 shows the 80-kyr high-resolution benthic record of the mid-Pliocene warm

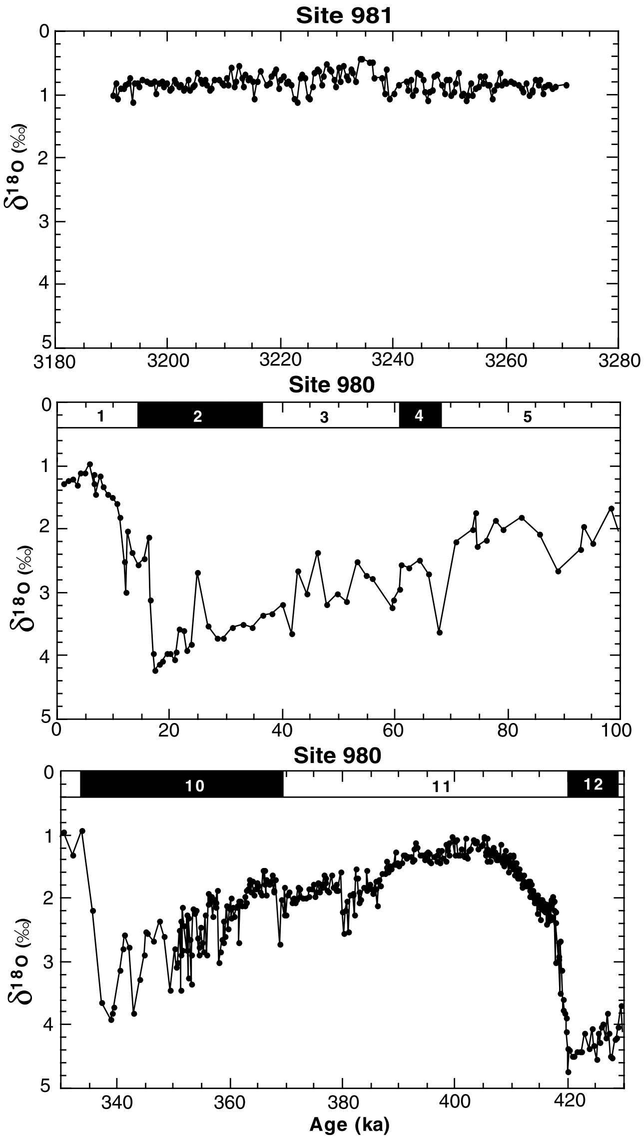


**Figure 6.** Comparison of planktonic $\delta^{18}O$ data from the mid-Pliocene warm period with the same 100 kyr sections shown in Figure 5. Data from MIS 1–5 and 10–12 are from Site 980 [*Oppo et al.*, 1998; *McManus et al.*, 1999]. The amplitude of millennial-scale variations in planktonic $\delta^{18}O$ during the mid-Pliocene warm interval is comparable to the amplitude of high-frequency variability within the Holocene (MIS 1) and MIS 11 interglacial intervals (0.1 to 0.3‰). During Pleistocene glacial intervals (e.g., MIS 10), the amplitude of millennial-scale planktonic $\delta^{18}O$ variability is substantially greater than during Pliocene and interglacial intervals (~1.0‰). The similarity between amplitude and pacing of high-frequency $\delta^{18}O$ fluctuations between Holocene, MIS 11, and mid-Pliocene records implies stability of surface conditions (a combination of SST and surface salinity) against a background of relatively warm global temperatures and low global ice volume.

period compared with two intervals from Site 980 [*Oppo et al.*, 1998; *McManus et al.*, 1999]; Figure 6 shows planktonic $\delta^{18}O$ from the same three intervals. These comparisons show the relative amplitudes of variation during Late Pleistocene glacial/interglacial cycles and during the mid-Pliocene over intervals of similar length. As discussed in section 1.1.1, other studies have found that suborbital variations during glacial intervals show substantially higher amplitude than during interglacials. Our results are consistent with this finding. Mid-Pliocene benthic $\delta^{18}O$ varies with a maximum amplitude of ~0.3‰; in contrast, millennial-scale benthic $\delta^{18}O$ excursions have an amplitude >0.4‰ in early Pleistocene and late Pliocene records [*Raymo et al.*, 1998; *McIntyre et al.*, 2001], and an amplitude of 0.2–0.8‰ during late Pleistocene MIS 10 (Figure 5). Where discrete events are apparent in our benthic $\delta^{18}O$ record (particularly from 3250–3270 ka) the pacing of benthic $\delta^{18}O$ variations is similar to the 1–4 kyr recurrence interval noted in other glacial and interglacial records (see section 1.1.1).

[32] It is noteworthy that although mid-Pliocene $\delta^{18}O$ is extremely stable relative to the 2‰ changes from glacial to interglacial conditions during the Pleistocene, the amplitude of high-frequency benthic $\delta^{13}C$ variation during the mid-Pliocene interval is comparable to the amplitude of high-frequency variability of Holocene and Pleistocene benthic $\delta^{13}C$ (Figure 5) (Raymo et al., submitted manuscript, 2003). The variability of NADW that is believed to drive benthic $\delta^{13}C$ in the North Atlantic during glacial fluctuations is most likely not a factor affecting mid-Pliocene $\delta^{13}C$ due to the extended warm interval and lack of North Atlantic glacial advances at that time. The lack of correlation between benthic and planktonic records, as well as between oxygen and carbon signals in each record, may suggest that no strong temperature-related forcing mechanism affected thermohaline circulation during the mid-Pliocene warm period. This contrasts with scenarios predicted for 21st century global warming by several modeling studies [*Manabe and Stouffer*, 1993; *Rahmstorf and Ganopolski*, 1999], in which warm conditions are associated with enhanced freshwater runoff and cessation of thermohaline circulation in the North Atlantic, resulting in long-term cooling. Alternatively, the substantial fluctuations in the Pliocene benthic $\delta^{13}C$ records may indicate that bottom-water variations occurred even in the absence of large changes in SST at Site 980/981. Raymo et al., (submitted manuscript, 2003) show that early Pleistocene $\delta^{13}C$ patterns at these sites are largely insensitive to regional climate changes.

[33] Our planktonic data also contrast with planktonic $\delta^{18}O$ records from glacial intervals (Figure 6). While *N. pachyderma* $\delta^{18}O$ varies with amplitude >1.0‰ during late Pleistocene glacial episodes [*Oppo et al.*, 1998], indicating SST fluctuations of 4–6°C [*McManus et al.*, 1999], planktonic $\delta^{18}O$ in the mid-Pliocene data show much lower amplitude of variation on millennial scales (0.1–0.3‰). Figure 6 shows the substantially greater amplitude of planktonic $\delta^{18}O$ fluctuation during glacial MIS 10 compared with interglacial MIS 11 or the mid-Pliocene interval. However, the 1–4 kyr pacing of planktonic $\delta^{18}O$ excursions

in our Pliocene record is comparable to that seen in glacial planktonic $\delta^{18}O$ [e.g., *Oppo et al.*, 1998].

### 4.4. Comparison of the Mid-Pliocene With Interglacial Intervals

[34] The low amplitude (<0.3‰) of high-frequency benthic $\delta^{18}O$ variation in our Pliocene record is similar to that recorded at Site 980 during the Holocene and MIS 11 (Figure 5). This is also comparable to the amplitude of benthic $\delta^{18}O$ oscillations in late Pliocene interglacial records [*McIntyre et al.*, 2001]; the ~2 kyr pacing during interglacial events seen by *McIntyre et al.* [2001] is similar to the ~2 kyr spectral peak in our benthic $\delta^{18}O$ record; Figure 4a). Figure 6 shows that the 0.1–0.3‰ variation in mid-Pliocene planktonic $\delta^{18}O$ is very similar to the amplitude of high-frequency $\delta^{18}O$ variations in *N. pachyderma d.* during the Holocene [*Bianchi and McCave*, 1999; *Chapman and Shackleton*, 2000] and during MIS 11 at Site 980 [*Oppo et al.*, 1998; *McManus et al.*, 1999, 2003]. The planktonic $\delta^{18}O$ fluctuations in the mid-Pliocene record are also similar in amplitude to those seen in late Pleistocene interglacial planktonic $\delta^{18}O$ [*Oppo et al.*, 1998].

[35] The similarities in benthic and planktonic proxies among mid-Pliocene, Pleistocene interglacial (MIS 11) and Holocene records (Figures 5 and 6) implies that the mid-Pliocene warm period effectively behaves like these other interglacial episodes, even though it is of much longer duration (>80 kyr). On millennial timescales, mid-Pliocene conditions reflect relative climatic stability, with low-amplitude variations in benthic and planktonic $\delta^{18}O$ that maintain an approximate recurrence interval of 1–4 kyr, comparable to the pacing of D-O and SST variations in Pleistocene records. The relative stability of planktonic $\delta^{18}O$, a proxy for surface hydrography (Figure 6) could only reflect large variations in SST if surface salinity varied simultaneously and with opposite sign; however, we infer stable surface conditions on millennial timescales to be more plausible.

### 4.5. Implications for Climatic Behavior During Warm Conditions With Low Ice Volume

[36] Our high-resolution data points to a relatively stable climate during the mid-Pliocene warm period, analogous to millennial-scale stability within the Holocene and MIS 11. Millennial-scale climate fluctuations appear to occur with reduced amplitude during warm episodes [see also *Oppo et al.*, 1998; *McManus et al.*, 1999, 2003; *McIntyre et al.*, 2001] and our results are consistent with the assertion by *McManus et al.* [1999] that glacial conditions represented by a sea-level decrease of ~20–50 m must be surpassed in order for large-amplitude millennial-scale variability to be evident.

[37] It has been suggested [*Broecker et al.*, 1990; *Weaver and Hughes*, 1994; *Driscoll and Haug*, 1998; *Bianchi and McCave*, 1999] that negative feedback mechanisms would place an upper limit on the duration and extent of North Atlantic warmth; that during warm intervals, freshwater input from an enhanced hydrologic cycle combined with melting of Greenland ice may eventually lower seawater salinity to the point where NADW production, and consequently heat flux to the pole, is reduced. The predicted results include rapid development of instabilities in thermohaline circulation [*Weaver and Hughes*, 1994] and potentially long-term cooling of the Northern Hemisphere [*Rahmstorf and Ganopolski*, 1999]. The low amplitude of variability in planktonic $\delta^{18}O$, combined with the lack of covariance between benthic $\delta^{13}C$ and benthic or planktonic $\delta^{18}O$, suggest that major thermohaline and climatic instabilities of the amplitude suggested above did not occur over long stretches of the preglacial Pliocene. The reduction in ice volume represented by a ~25 m mid-Pliocene sea-level elevation (relative to modern conditions) apparently did not trigger such negative feedbacks.

[38] The persistence of a relatively stable climate during a prolonged warm period has important implications for possible 21st century climate scenarios. It is estimated that, if the rate of greenhouse gas emission continues to rise at the present rate, global average temperature will increase by approximately one quarter of a degree Celsius every ten years, or 2.5°C per century [*Houghton*, 1997]. Within one hundred years, global temperatures could approximate those maintained during the Pliocene warm interval. The feedback mechanisms controlling global climate response to anthropogenic addition of greenhouse gases are extremely complex, and predictions of potential climatic reactions cannot be made with certainty. However, the results of this study indicate that the climate of the North Atlantic region may be relatively stable during an extended warm period with low ice volume. Colder temperatures and/or higher ice volume seem necessary conditions for high amplitude climate variability on millennial timescales.

## 5. Summary and Conclusions

[39] Analyses of $\delta^{18}O$ and $\delta^{13}C$ in benthic and planktonic foraminifera in an 80-kyr North Atlantic sedimentary sequence from the mid-Pliocene warm period reveal that although millennial-scale fluctuations exist in these records, they occur with low amplitude compared with millennial-scale variations that occur during glacial times. The mid-Pliocene warm period thus appears to have been an interval of relative climatic stability, similar to more recent warm intervals such as the Holocene or MIS 11. The Pliocene warm period effectively behaves like an extended interglacial interval. The results of this work support other research that has suggested that warm temperatures and low global ice volume may dampen high-frequency variations within the climate system, imposing relative stability on millennial timescales. These findings may facilitate prediction of climatic response and sensitivity to anthropogenic perturbations of the hydrologic cycle at high northern latitudes.

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